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Procedia CIRP 34 (2015) 193 – 198

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9th International Conference on Axiomatic Design – ICAD 2015

A preliminary check of the refurbishing large office buildings to a zero energy condition

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Abstract

The sustainability in the building industry is currently a trend of the governmental policies in the EU and the USA. In the EU, the target for 2020 is to achieve net-zero energy buildings (NZEB) for the new constructions, as enforced by the 2010 recast Energy Performance Building Directive. On the other hand, it is necessary to make decisions about the technologies to include in buildings when undergoing a major renovation. The aim of this paper is to help to define guidelines about the feasibility of achieving a near-zero energy condition on the existing building stock using the Axiomatic Design theory. Applying this design process to a set of existing office buildings, it is possible to evaluate the energy use of renovated buildings. In the context of this study, the renovation focuses on the reduction of internal loads, isolating the facade and applying new efficient systems in each building. Following the decoupled design matrix of such renovation, it is possible to obtain the fuzzy functions of the energy use. In reality, these functions are the fuzzy sum of contributions to the energy use of the design parameters applied according to the design matrix. The membership function of the energy use allows in turn determining the information content of each type of building, for a design limit of 100 kW·h/(m^2·a) of primary energy use. It is found that a renovated building using a photovoltaic system area of about 20% of the floor area of the building allows achieving null information content, or in other words a 100% probability of success.

Peer-review under responsibility of the organizing committee of 9th International Conference on Axiomatic Design

Keywords: NZEB; Energy Technologies; Decoupled designs

1. The NZEB concept

The recast of the Energy Performance Building Directive (EPBD) [1] caused some important changes in the building market, by enforcing the concept of near-zero energy buildings (NZEB). Actually, all the new European buildings must be NZEB after December 2020, as well as all buildings used by public authorities after December 2018.

According to the new directive, a NZEB will be a very energy efficient building, with the needs of energy covered at a large extent by renewable sources. The directive also applies to the existing buildings when undergoing a major renovation.

This paper intends to find preliminary indicators for the feasibility of achieving a near-zero energy condition when already existing buildings are subjected to a major renovation. Indeed, in the following years the society will envisage new technologies that can fulfill the needs of a building with just a fraction of the current use of energy.

Actually, many new technologies and applications that are able to recover and to store heat, as well as to produce electricity are arising [2].

According to the principles of thermodynamics, the energy degrades from power or from heat at high temperature to heat at low temperature. Therefore, in a thermodynamic system there is always room to recover heat at low temperature, making it relatively easy the use the heat for domestic hot water or for space heating applications. On the contrary, non-domestic buildings claim for cooling, because of the heat

Peer-review under responsibility of the organizing committee of 9th International Conference on Axiomatic Design
doi:10.1016/j.procir.2015.07.054

produced inside, as well as for the production of electrical energy.

The net zero energy buildings concept, differs from the near-zero idea by assuming the possibility of an average zero balance instead of a range of acceptance.

According to the EPBD, it is a responsibility of the Member States (MS) to define the limit for the primary energy consumption. The limit of primary energy should allow achieving the cost optimal solution obtained between the net present value of the infrastructure and the cost of the energy during a time frame [3].

Both concepts of energy buildings have to do with time boundaries, space boundaries and energy definitions [4]. The common time boundary is the average year, but many authors claim for life cycle assessment by introducing the energy content of the construction materials and maintenance, as well as the energy for demolition and recycling [5].

The near-zero balance might be achieved with the help of renewable energy produced inside the footprint of the building, in spaces close to the building or offshore the building area. It is especially important to design a very efficient building in the instance of producing renewable energy on-shore [6].

In a wider view, the balance may take into account the renewable energy content of the national electrical network, making it easy to achieve a NZEB.

The zero or near-zero energy target may take into consideration the utility energy coming in and going out the building, thus forcing the renewable production on-site to match the amount of energy that is used in the building. Another possible balance uses the primary energy and the conversion multipliers between the final energy and the sources of energy. It is worth noticing that the primary energy balance requires the support of the national electrical grid, making it not free from carbon emissions [7]. Therefore, achieving a net or nearly carbon free building will be a much more challenging approach.

The EPBD uses the model of primary energy, expressed in kW·h/m^2 per year, and requires converting the final energy in primary energy by using the primary energy factors (PEF). The average PEF of the EU-28 is close to 2.5 [8], but in countries with half of the electricity coming from renewable energy sources (RES), PEF is lower than 2.

This paper will follow the net-zero and near-zero energy interpretation proposed by REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) task force [9], following the flows of energy that are depicted in Fig. 1. As such, the building, all the related technical systems and the RES are located inside the control volume that is used to evaluate the balance between the input and the output primary energy. The flows of energy might ensure the needs of a "typical use of the building" *i.e.*, to ensure the requirements of heating, cooling, hot water, ventilation, lighting and the energy for appliances.

Some latest studies, as well as the transcription of the directive to the regulations of the MS, indicate a value of 110 kW·h/(m^2·a) for the primary energy in Estonian houses [3]. A NZEB benchmark study on hotels found a likely value of 117 kW·h/(m^2·a) for the primary energy for hotels in France, 71 in Italy and 72 in Spain [10].

In 2014, the MS definitions of NZEB state that the primary energy for office buildings could go from 40 kW·h/(m^2·a) in Flemish Belgium to 110 in France, explicitly stating that this applies to offices with an installation of air-conditioned.

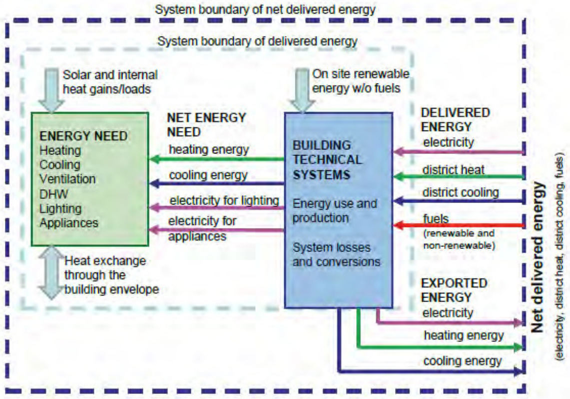

Fig. 1. Building boundary and energy balances (from [8])

Moreover, the same study shows some results for pilot office buildings that go from 44 to 68 kW·h/(m^2·a) in France and Holland [11].

To address the NZEB in the renovating stock, this paper uses the information contents calculated with the systems' functions of the energy distribution of a set of five existing buildings. The function of each building arises from the sum of the contributions of the technological parameters, tuned in a sequence defined by the design equation. Section 2 highlights the design equation and theorizes the way of calculating the information, while sections 3 and 4 apply this approach to the five buildings.

2. The design equation

In this section, the design equation [12] is set for NZEB and a theoretical approach to get the system function is developed using fuzzy numbers. Checking where the information is nil, will give indicators for the feasibility of achieving a near-zero energy building.

The EPBD and the REHVA guidelines for achieving NZEB focus on the need of reducing the internal loads of the building, prior to applying other techniques. The energy consumed in a building also depends on the building envelope, the EU trend being the increase of the buildings' isolation. Furthermore, it is helpful to choose very efficient lighting control systems and heating, cooling and related systems, leaving to RES the production of the remaining energy needs.

There are some contributions of AD to the building industry [13] and to the eco-design [14, 15] areas of research that will benefit from the framework of AD. One of the key tasks of these contributions is the correct setting of the functional requirements (FRs) [16] to express the design equation [17]. In this paper the authors identified the following high level functions:

- FR_1: Reduce the internal loads;
- FR_2: Adjust the building envelope;
- FR_3: Reduce the energy consumption of systems;
- FR_4: Produce locally the energy.

The corresponding design parameters (DPs) will be:

- DP_1: Internal loads (which should be made small by

adjusting the occupancy, the lighting system and the appliances);
- DP_2: Overall transmittance coefficient and solar factors of the building;
- DP_3: Lighting control and air conditioning systems (which should be efficient);
- DP_4: Renewable Energy Sources

Usually, a better envelope will reduce the needs of heating, while increasing the needs of cooling, which makes the right choice of this system somewhat dependent of the internal loads. Anyway, the overall transmittance of the building may play a key role in a NZEB, because the overall internal load will be lower when compared to a common building.

On its whole, the type of the technical systems of a certain building might be selected according to RES, since it may depend on the recovery of heat from RES. The type of technical systems is independent of the building and of its use, as well as from the type of RES.

The following equation expresses the aforementioned dependencies, where "*X*" and "*x*" stand for strong and for weak relationships, respectively:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} X & & & \\ x & X & & \\ & & X & X \\ & & & X \end{bmatrix} \cdot \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \quad (1)$$

On the other hand, if one wants to define the power of the systems and the use of energy, then the design equation will change. As a result, the consumption of the lighting control and of the thermal systems will depend on the internal loads and on the transmittance of the building envelope. At last, the RES should fulfill the needs of the building, which depend on the consumption of all the other systems. The sensitivity of the FRs to the changes of the DPs is found by applying finite differences to the new design equation, giving rise to Eq. 2.

$$\begin{bmatrix} \delta FR_1 \\ \delta FR_2 \\ \delta FR_3 \\ \delta FR_4 \end{bmatrix} = \begin{bmatrix} X & & & \\ x & X & & \\ X & x & X & \\ X & x & X & X \end{bmatrix} \cdot \begin{bmatrix} \delta DP_1 \\ \delta DP_2 \\ \delta DP_3 \\ \delta DP_4 \end{bmatrix} \quad (2)$$

Equation 2 shows a decoupled design, meaning that changing DP_i might occur after DP_{i-1} has been settled. This is a very common process in engineering calculations, making the achievement of the FR function presented in this section useful for other engineering applications. In fact, the contribution of a DP subjected to the tuning of the prior ones, is the difference between two successive results of a simulation which allows getting the required functional result.

Therefore, let E_0 be the overall energy use of a building in a standard nominal state of operation. The overall energy will change to E_1 due to the variation δDP_1. The value of the energy will change to E_2 by setting up DP_2 through a change δDP_2. The difference between two successive values of the use of energy, E_{i-1}–E_i, is due to the impact of δDP_i assuming the prior settings of all the former DPs, as shown on Eq. 3.

$$\Delta_i(\delta DP_i | \delta DP_{j,(j=1,i-1)}) = E_{i-1} - E_i. \quad (3)$$

All the evaluations of the use of energy encompass errors. One can deal with those errors by fuzzifying E_i through a membership function (MF) μE_i, converting Eq. 3 into a fuzzyfied form according to Eq. 4.

$$\mu\Delta_i = \mu E_{i-1}(-)\mu E_i. \quad (4)$$

As a consequence, the MF of the energy use related to all the *n* DPs is given by the fuzzy nominal energy minus the fuzzy sum of the variations, as per Eq. 5.

$$\mu E = \mu E_0(-)(\textstyle\sum_{i=1}^{n})\mu\,\Delta_{i-1} \quad (5)$$

Otherwise, it is also possible to obtain the MF $\mu\Delta_i$ on a basis of experience and of prior indicators.

Interestingly, Eq. 5 is a way to achieve the MF of a design, knowing the previous μE_0 and estimating the MF of the variations $\mu\Delta_i$ due to the DP setting. Notice that in a decoupled design the sequence of obtaining $\mu\Delta_i$ might be according to the sequence of the DP tuning expressed in the design matrix.

This fact shows the importance of getting the design equation prior to evaluate the MF, hence closely relating the AD's axioms 1 and 2.

The fuzzy function of the energy allows computing the information content, taking into account the common area of the membership function and the area of the whole system range. The areas are computed using the membership function of the energy use in the universe of discourse, according to Eq. 6, where *L* is the upper limit of the energy use.

$$I = \log_2\left(\frac{\int_{-\infty}^{+\infty}\mu E(x)dx}{\int_{-\infty}^{L}\mu E(x)dx}\right). \quad (6)$$

3. The energy performance of the buildings

The energy use in a building is shared mainly between appliances, lighting and air-conditioning (HVAC). Accordingly, the feasibility of a near-zero energy building will increase with the spread of new led technologies for lighting, new low energy computers and appliances, more efficient HVAC systems and more efficient office systems. In what concerns to the production of energy, RES are becoming more efficient, the new photovoltaic (PV) multi-junction cells allowing currently achieving efficiencies higher than 40%. This will make possible to supply almost all now-a-days three to five-story buildings using PV panels covering the whole roof.

3.1. How the buildings were evaluated

To check the feasibility of achieving a NZEB, this paper studies the refurbishing of five different existing buildings, exposed to the same density loads. The buildings are located in the middle area of Portugal. This area belongs to the Ecofys EU climatic zone two, which contains most of the central zone of Portugal and Spain, south of France, most of Italy, the western Balkans and the north of Greece.

Table 1 shows the locations of buildings B_1 to B_5, their dimensional characteristics and their annual final energy use. Building B_1 is a common office floor in a town building; B_2 and B_4 are switching centers of telecommunications with the associated offices; B_3 is a large detached building of a public observatory organization and B_4 is also a public building.

The buildings have shape factors from 0.2 to 0.66, a relation between the outside area and the volume of the building. The higher the shape factor, the more the outdoor climate impacts the indoor conditions. As they cover a wide range of shape factors, it allows to check the influence of the external environment on the energy consumption.

Table 1. Characteristics of the buildings and final energy use.

	B_1	B_2	B_3	B_4	B_5
Location	Lisbon	Santarém	Lisbon	Setúbal	Setúbal
-Floor Area [m^2]	593	2692	4392	3679	937
-Shape factor [m^{-1}]	0.2	0.3	0.41	0.48	0.66
-Roof Area [m^2]	100	540	1290	1430	210
-Electricity used [kW·h/a]	NA	1214102	812950	1558713	NA
-Electricity model with actual profile [kW·h/a]	NA	1294233	833267	1451355	NA

These buildings underwent a certification process according to the former transcription of the EPBD to the Portuguese rules and regulations. For certification, it is required to model the actual performance of the building, after which the building is classified according to its response to a nominal set of loads and schedules.

The electricity used (row five of Table 1) is evaluated by averaging the values of the invoices of the last three years before the certification. At the time of the certification, the records on previous electricity consumption of building B_1 and B_5 were not available because they were freshly refurbished.

Table 1 also expresses the goodness of the models by showing similar values from the consumed electricity and the electricity obtained in the thermal models using the so-called actual profiles.

To find an actual profile, one has to check the dimensions of the elements of the building in the blueprints and in the site, in order to estimate the real thermal characteristics of the building. At last it is necessary to survey all the electrical equipment and to measure the consumption of the most important systems.

Next, all the dimensions and the thermal definitions of the building are set in a thermal analysis computer program. In this case, we used Energy Plus™ with the Design Builder™ interface. All the schedules and powers of the room equipments were introduced, so that the average annual consumption of "room electricity", lighting, heating and cooling could be computed, inter alia. A post process operation, allows accounting all the devices not included in the analysis program.

3.2. Setting the loads

The thermal models described in the former section allow computing the energy use of each one of the five buildings at any new load condition. For the purpose of certification, the models are employed to calculate the use of energy at pre-defined nominal power densities and schedules.

E_0 represents the first set of calculations at the nominal conditions according to the certification rules. Regarding B_2 and B_4, the switching centres were considered as similar to offices, in order to allow comparing the results.

Hence, the buildings undertook a similar calculation process by setting forth the variations of each DP and getting the energy needed for running the building at those conditions. In order to set DP_1, the occupancy changed to 12 m^2 per occupant, the room loads for all office equipment was reduced to 4 W/m^2 and the light power was shortened to 5 W/m^2. In reality, ASHRAE (American Society of Heating Refrigeration and Air-Conditioning Engineers) states that room loads may vary from 3.55 to 5.38 W/m^2 at 11.6 m^2/workstation, with laptops at the workstations and a shared multi-propose printer for each set of ten persons [18]. Achieving a low light power requirement is possible by means of LED technology, alone or in combination with fluorescent lighting.

Table 2 shows the results of uses of energy, E_0 to E_3, just for building B_3, which is a realistic large edifice with an average shape factor.

Table 2. Final energy use for building B_3 with the DPs' changes

	Room electricity [kW·h /a]	Lighting [kW·h /a]	Heating electricity [kW·h /a]	Cooling electricity [kW·h /a]	Total electricity [kW·h /a]
-E_0:Nominal load	197264	88024	81478	221056	634237
-E_1:Reduced load	50624	48905	100765	183688	436401
-E_2:Reduced load + U	50624	48905	97388	191421	440757
-E_3:Reduced load + U + efficient	50624	26647	52751	88693	258539

The column "Room electricity" of an office building accounts for computers, telephones and other appliances; "Lighting" accounts for the use of energy for lighting the spaces at a 450 lux illuminance; "Heating electricity" accounts for all equipment, heat pump, fans and other equipment, necessary for maintaining the rooms at a minimum of 20 ºC during the working hours; "Cooling electricity" accounts for ensuring the Summer comfort temperature of 25 ºC, accounting with the energy in chiller, and auxiliary equipment during the cooling period. The estimation of E_0 to E_2 accounts for the performance of the refrigeration equipment on site, while E_3 accounts for an efficient cooling and heating device.

In the simulations E_0 and E_1, U is the estimated value on site of the global conductivity of the wall, with values between 1.0 and 1.5 W/(m^2 ºC). In the E_2 calculation U was set close to 0.5 W/(m^2 ºC), in accordance to the reference values of the new thermal regulation [19]. In the calculations, no changes occur in the windows as they already follow the solar factors and the conductivity as prescribed in the new regulation.

Finally, the "Total electricity" sums all the aforementioned energies plus the use of energy in various equipments of the HVAC system, the energy for lifts, garages and for all the other appliances not included in the former categories. At last, E_3 represents the energy use by employing the new efficient systems. For this evaluation, it was set a more performing lighting system and a more efficient HVAC system. In the former, it was adopted a dimming control system in order to vary the lighting power taking into account the light entering through the windows.

Concerning the HVAC, it is now affordable to use systems with a yearly overall efficiency of 4.5 on cooling and of 4.0 on heating. As for ventilation, the choice felt on using units with a specific fan power of 500 W/(m^3/s) on supply and return, which corresponds to the best class according to EN13779 [20]. Moreover, one assumes the use of variable flow in the water network and variable airflow in the terminal devices, which will cut to half the use of energy in these devices.

3.3. Results by varying the DPs

Achieving the MF of the primary energy for each building needs evaluating the energy use in the nominal condition and in the further three conditions. Next, applying a PEF of 2 and dividing by the area of the building, one obtains the needs of primary energy according to the EPBD in an average climate year. Table 3 expresses the results:

Table 3. Primary energy in [kW·h/(m^2·a)] for the DPs' changes

	B_1	B_2	B_3	B_4	B_5
-E_0:Nominal load	372	299	289	295	292
-E_1:Reduced load	178	176	199	153	196
-E_2:Reduced load + U	178	168	201	147	189
-E_3:Reduced load + U + efficient	123	123	118	117	117

As expected, the decrease in energy in office buildings depends rather on the heat loads and on the efficiency of the systems than on isolation.

3.4. The PV production

The most common RES in cities is the PV system, because it is easy to install, it is modular and it fits the architecture. To avoid shades is an important issue when installing PV panels in order not to cause extra electrical resistances in the PV circuits. In this study, avoiding shades is feasible on all buildings except B_5, which is located close to high buildings.

Conversely, wind energy devices are more difficult to install and use, because of the atmospheric boundary layer and noise problems associated. Nevertheless, building B_3 would be a good candidate to install wind devices as it locates close to a river. Other renewable systems for producing electricity need the transportation of matter to the building, so that they are out of some definitions of RES. The choice of this paper is to use horizontal PV panels with an overall efficiency of 17%. Horizontal panels fit better in the architecture of the buildings.

Nevertheless, this disposition reduces the global production of electricity by about 15% regarding an optimal inclination of the panels. The horizontal average sun radiation in a year is 1568 kW·h/(m^2·a) for Lisbon, 1555 for Santarém and 1600 for Setúbal.

4. The information content

All energy results from a thermal simulation program may vary in a range of ±10%. Therefore, the energy at nominal conditions E_0 varies in a range of 10% around the calculated point. As such, one can assign a fuzzy triangular function to E_0 with membership nil at the limits "a" and "b" of the range and a core "m" with unitary membership at the calculated value.

The membership function at reduced loads (E_1) may have a similar behavior to E_0, so that it is possible to find $\mu\Delta_1$ according to Eq. 4. On the other hand, setting $\mu\Delta_2$ depends on the influence of the isolation, whose thermal resistance may drop by 30% depending on the thermal bridging. As a result, $\mu\Delta_2$ is set as a triangular function with a lower limit "a" 30% less than the core and an upper limit "b" equaling "m". The core value "m" is set by subtracting E_2 to E_1. A similar reasoning applies for reaching $\mu\Delta_3$, by assuming "a" as 20% less than the core value and "b" equaling to the core. Actually, EUROVENT, the European Committee of the Air Handling and Refrigeration Manufacturers, accepts a variation up to 15% in the efficiency of the refrigeration system. In addition, the control systems and the human behavior may play an important role in the energy use, which makes it possible a reduction of 20% in the performance of the entire system.

Applying Eq. 5 to the data of Table 3, and taking into account the described calculations, one can compute μE_3. Using again building B_3 as an example, the nominal fuzzy energy states as $\mu E_0=T(260;289;318)$, the reduction of introducing all DPs is $\mu\Delta_{1\text{-}3}=T(106;171;220)$, which allows obtaining $\mu E_3=T(40;118;211)$, where T stands for the triangular membership function. Likewise, Table 4 shows the parameters of the triangular MF for all the buildings.

Table 4. Triangular fuzzy membership μE of primary energy [kW·h/(m^2·a)] before the incorporation of RES

	B_1	B_2	B_3	B_4	B_5
-a	31	45	40	43	39
-m	123	123	118	117	117
-b	226	212	211	199	211

To be able to reduce the energy use to a near-zero value it is necessary to provide energy. In this study, the mentioned PV system with 17% nominal efficiency lets to define a triangular MF stated as $\mu PV=T(0.15;0.17;0.17)$. Getting the annual energy provided by the PV system and subtracting it from the MF of Table 4 allows obtaining the MF of the energy use of each building.

In the absence of regulations, the primary energy limit for an NZEB was set as 100 kW·h/(m^2·a). Using the MF of each building, it is then possible to calculate the information content of each design.

Figure 2 depicts the information content for each value of the relation between the PV area and the floor area. The information function runs until a PV area equal the roof area of each building. Notice that the total use of the roof may be difficult to achieve due to the installation of various technical devices on it.

The shape factor of the buildings has no clear influence on the information content. Moreover, Fig. 2 expresses that all buildings attain zero information content as long as the available roof area for the PV installation is about 20% of the total floor area of the building.

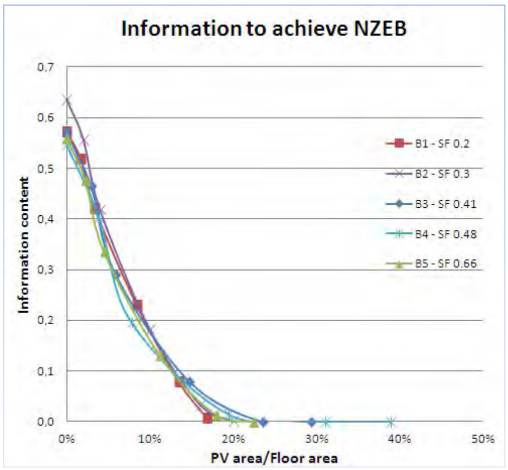

Fig. 2. Information of the system for different shape factors depending on the available area for installing PV

5. Conclusions

This paper helps to check the feasibility of attaining a building with near-zero energy (NZEB) needs, when an existent office building undergoes a major renovation. It was found possible in buildings in the Ecofys climate zone two, as long as the photovoltaic (PV) panel area reaches 20% of the floor area of the building. It is also necessary that the building has a low internal load, with appliances density of 4 W/m^2 and a lighting density of 5 W/m^2. Moreover, the office building might be refurbished using an efficient control light system and an efficient air conditioning system. The overall use of primary energy in the building was set to 100 $kW{\cdot}h/(m^2{\cdot}a)$ with a the primary energy factor of 2.

Peculiarly, the isolation and the shape factor of a building have a reduced influence in the energy use of the building, or in other words, the influence of the external conditions is a minor factor to achieve a NZEB in this climate zone. This conclusion makes it possible to use the same primary energy indicator to define a NZEB in slightly different climatic areas. Besides, it shows that it is somehow useless to increase the insulation of renovated office buildings, as the current trend dictates.

Regarding the Axiomatic Design theory, this paper gives a contribution on how to define the system behavior function for decoupled designs. In reality, it may be possible to define the fuzzy membership function (MF) for the performance of a system when dealing with the first design parameter (DP_1). Then the MF of the design is achieved by adding in sequence the MF contribution of each of the following DPs, according to the sequence expressed in the design matrix.

Acknowledgements

The authors gratefully thank the sponsorship of *Fundação para a Ciência e Tecnologia* through the Strategic Project UID/EMS/00667/2013 – UNIDEMI.

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